Optical Tailoring of xFEL beams

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There is an inherent flexibility unique to free electron lasers (FELs) that lends well to experimental approaches normally too difficult for other light sources to accomplish. This includes the ability to optically shape the electron bunch prior to final its acceleration for the final FEL process. Optical pulse shaping of the electron bunch can enable both femtosecond and attosecond level FEL pulse control. Pulse shaping is currently implemented, not optically but mechanically, in LCLS-I with an adjustable foil slit that physically spoils the momentum phase of the electron bunch. This selectively suppresses the downstream FEL process of spoiled electrons. Such a mechanical spoiling method fails for both the soft x-ray regime as well as the high repetition rates that are planned in LCLS-II. Our proposed optical spoiling method circumvents this limitation by making use of the existing ultrafast laser beam that is typically used for adjusting the energy spread for the initial electron bunch. Using Fourier domain shaping we can nearly arbitrarily shape the laser pulses to affect the electron bunch. This can selectively spoil electrons within each bunch. Here we demonstrate the viability of this approach with a programmable acousto-optic dispersive filter. This method is not only well suited for LCLS-II but also has several advantages over mechanical spoiling, including lack of radiation concerns, experiment specific FEL pulse shapes, and real-time adjustment for applications that require high duty-cycle variation such as lock-in amplification of small signals.

I. INTRODUCTION

Our aim is to provide pulse shaping capability to the x-ray Free Electron Laser (xFEL) at SLAC's Linac Coherent Light Source (LCLS). Optical pulse shaping has been a standard practice in the ultrafast laser community for decades. Temporal control of beam intensity is crucial for pump-probe experiments in Molecular-Optical (AMO) experiments and non-linear optical processes.¹ The current "shaping" system consists of adjustable-width foil slits which act to physically alter the electrons' momentum distribution. With the construction of LCLS-II the foil system will have to be replaced since the 100 kHz-1Mhz high repetition rates would destroy the foil.

In this work, we implement a Acousto-Optic Programmable Dispersive Filter (AOPDF) "Dazzler", by Fastlite, to demonstrate our ability to optically shape the xFEL pulses by modulating the initial electron bunch. The current LCLS is equipped with a laser heater to prevent microbunching in the accelerator², which can be manipulated to shape the electron bunch. Similar optical-based xFEL shaping has been demonstrated at FERMI³ using an interferometric method. While simple and robust, this method lacks fine control over the electron bunch. Alternatively, by applying traditional Fourier shaping via time-varying phase-amplitude masks to the heater laser allows us to produce optically adjustable, time-varying control of the electron bunches. This in turn produces the shape controlled xFEL output.

II. MODELING

The first step was to model the optical system. The injector setup has the driving laser ("oscillator"), a 100fs mode-locked Ti:Sapphire unit operating at 800 nm, stretched to 200 ps by a pair of gratings, through a regeneration amplifier (regen), an active regenerative amplifier (MPA), and a matched grating compressor to re-compress the pulse. The compressed beam is then sent to 253nm in a frequency tripling stage and sent to the photocathode gun line. The spent 760 nm pulse is used for the laser heater. It is stretched to 20 ps in order to promote even energy distribution across the 3 ps electron bunch. For our case, we use only a 4 ps pulse to sufficiently cover this electron bunch but using the pulse shaping to adjust the intentionally uneven energy distribution for finely written features that affect the bunch.

To preserve the the photocathode pulse, we will block the heater beam from the main drive laser and use it exclusively for the photocathode. Our setup will then use the identical backup laser but with its photocathode beam remaining blocked. The backup oscillator will first pass through the pulse shaping Dazzler and then be amplified. This beam will finally be compressed and routed around the uv generation stage normally used for photocathode beam. Thus, rather than using spent beam for the heater, we will use the main 760 nm beam directly for the heater, along with its Dazzler controlled temporal shape. Both lasers are synchronized together using RF locking with an arbitrary relative delay, so there will be negligible timing jitter between the two lasers systems.

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A Matlab script was written to simulate the addition of an amplitude and phase shaping filter. It can input a measured spectrum (such as the direct oscillator output) or default to a Gaussian spectrum of specified width. The Dazzler accepts both direct spectral input via text files, or adjustments through the integrated GUI sliders. Phase is specified in terms of Taylor polynomial coefficients. The Matlab script accepts both polynomial and sinusoidal phase inputs. In order to split the electron bunch into two bunchlets while retaining the fixed lengths of each bunchlet, a heater shape shown in FIG. 1 is likely necessary. Using the script, we determined such pulse shapes are feasible with the Dazzler unit (figure 2).

FIG. 1. The approximate electron bunch shape and predicted necessary heater shape for two-bunch splitting

FIG. 2. The predicted temporal output from our system. The combination of phase and amplitude masking allows controlled modulation of pulse and notch widths. The asymmetry comes from asymmetry in the oscillator spectrum. Using a computer to adjust parameters iteratively can create more symmetric shapes.

III. DAZZLER CAPABILITIES

In order to have a good feasibility demonstration, we needed the Dazzler to be capable of producing a wide variety of shapes. Our Dazzler is a first-generation unit which lacks some of the capabilities of the current fourth-generation models, so we characterized its performance. The primary spectral feature we are writing is a Gaussian notch, so we tested the Dazzler's ability to resolve notches. Using the full oscillator output, we wrote notches from 0 nm to 20 nm FWHM (in 0.5 nm increments), centered to the oscillator bandwidth and the bottom of the notch set to zero intensity, and spectrometer recorded the throughput spectra. For notches greater than 3 nm FWHM the Dazzler's output matched the predicted output to within 5%. Narrower than 3 nm, the notch became more and more shallow until there was effectively no notch (about 0.5 nm FWHM). The Dazzler software only recognizes 0.1 nm resolution data inputs, which could be the cause of issues when dealing with very narrow notches.

FIG. 3. Sinusoidal phase is an attractive option for multi-bunch splitting, but the Dazzler introduces noticeable amplitude mask affects when high-frequency sine phase is applied. The upper and lower images are normalized to the same value.

We also tested the Dazzler's ability to apply large amounts of phase, both sinusoidal and polynomial. Due to being diffraction-based, there is some phase-amplitude cross talk which ranges from mild to severe. Figures 3 & 4 depict two of these issues. Applying a sinusoidal phase is useful for splitting the throughput signal into multiple peaks, but there is noticeable periodic fringing in the transmitted amplitude, thus indicating the phase and amplitude cross-talk in the Dazzler crystal. When enough phase, polynomial or sinusoidal, is added that the transform-limited pulse duration exceeds 15 ps (Dazzler GUI's time domain limits) there begins to be spectral clipping in the crystal. This clipping is well-estimated by the Dazzler unit. The plot in figure 4 is clipping when assuming the bandwidth is 100 nm—considerably wider than the oscillator output. The Dazzler is traditionally set to a very wide pulse in order to not clip the spectrum (The dazzler's "predicted spectrum" is actually a normalized transfer function), but when applying large amounts of phase it is beneficial to reduce the spectral width. This can lead to less overall clipping and more predictable behavior from the Dazzler unit.

FIG. 4. Introducing large amounts of quadratic phase caused edge clipping on the throughput spectrum. The Dazzler software is aware of this effect and gives a warning that predicted clipping around 775 nm and 826 nm, accurately matching our measurements.

IV. FUTURE WORK

Our next step is to install the Dazzler in the LCLS injector laser system to prepare for the LCLS restart in late September. To minimize invasiveness, the backup laser will be reconfigured with the Dazzler in conjunction with two magnetically-mounted mirrors that will allow bypass of the Dazzler. This provides for the circumstance where the primary injector laser fails and the backup laser must be returned to the standard, non-Dazzler, configuration. Beam time for this experiment is scheduled for October 2015, to test two-bunch splitting using the Dazzler.

Adjustments to the heater beam line are also necessary. The act of blocking spectrum automatically causes an increase in temporal pulse width, so the final stretcher will overstretch the pulse. This can be resolved two ways: Bypass the final stretcher, or adjust the post-MPA compressor. Simply adjusting the post-MPA compressor away from $d = 0.406m$ nominal separation to $d = 0.326m$ zeros the quadratic phase (the principle contributor to pulse width) causing the least effect to pulse timing, but leaves $\approx 210^7 fs^3$ unwanted cubic phase. This is at the very limit of the Dazzler's ability to remove, without introducing spectral edge clipping. We predict that the ultimate LCLS-II implementation will require a timed bypass of the final stretcher.

To prevent damage to the Dazzler's crystal it must be installed directly after the oscillator output, before the regen and MPA. The new setup is shown in figure 5.

FIG. 5. The new injector room optics setup directly after oscillator output. The boxed mirrors are on magnetic mounts, able to be removed to bypass the Dazzler entirely. The Cross Correlator is not necessary for the Dazzler as the beam is not being split for the photocathode gun.

The limitations introduced by the Dazzler unit are not well-suited to the end goal of arbitrary pulse shaping in LCLS-II. Alternatives exist that could provide higher-resolution control and operate without significant phase-amplitude crosstalk. The traditional approach is using a spatial light modulator (SLM) in conjunction with a pair of gratings to spatially spread the laser spectrum (figure 6).

The next steps will include an experimental setup implementing a spatial light modulator in conjunction with a Frequency Resolved Optical Gating (FROG) setup for measuring output pulse shape. This will let us run end-to-end simulations on how the pulse shape affects the electron bunch and output x-rays, using software previously developed at SLAC.

The rough order of work is enumerated below.

- Demonstrate multiple pulse generation (October Experiment).
- Use the existing Grenouille (FROG) at Rose-Hulman to measure time domain control of notches

Type	Resolution [pixels]	Refresh Rate [Hz]	Pixel Pitch [μm]	Array Size [mm x mm]	Cost per Unit
Reflective SLM	1x12,228	200	1.6	19.6 x 19.6	\$21,950
Transmissive SLM	1x640	25	100	64.0 x 5.0	\$30,950
Transmissive SLM	1x128	25	100	12.8 x 5.0	\$16,320

TABLE I. The quantitative specifications of each SLM type.

FIG. 6. An example setup for a transmissive SLM. Modern LCD SLMs allow rapidly time-varying phase and amplitude control.⁴

(dark solitons through amplitude shaping, π phase flips) for use if FEL end-to-end simulations.

- Look for non-linear soliton-soliton interaction (pre-emptively find the bugs). Though interesting, may complicate the desired process.
- Build a replica optical system as proposed for the LCLS heater shaping R&D project.
 - Coordinate equipment sharing with Alan Fry

VI. CONCLUSION

We have demonstrated the viability of the Dazzler as a control unit for optically-based x-ray pulse shaping. The limitations of the Dazzler suggest future work be done with a high resolution spatial light modulator.

(SLAC)

- \$30k for phase+amp shaper
- \$20k stretcher (depending on pre-existing parts)
- Implement phase only, amplitude-only, and both shaping. FROG the results as are interesting for LCLS.
- Work remotely with SLAC accelerator R&D group to run end-to-end simulations of those pulse shapes.

For its implementation in LCLS-II, we plan to develop a machine-learning program to take XTCAV x-ray output measurements and correlate them with phase and amplitude mask. This will eliminate the time-consuming process of manually adjusting mask parameters and enable a higher degree of x-Ray pulse control.

V. FEASIBILITY OF SLM OPTIONS

Reflective and transmissive SLMs from Meadowlark Optics are being considered. The quantitative merits are recorded in table I. Newer-model Dazzlers have been considered, but the phase-amplitude crosstalk is something intrinsic to AOPDFs and will still exist in more modern units. The optical setup is comparable for each SLM.

VII. BIBLIOGRAPHY

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